Injection-Controlled Tuning of an Electron-Beam Excited XeF($C \rightarrow A$) Laser

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Abstract—**Efficient, ultra-narrow spectral output from an electron-beam excited XeF($C \rightarrow A$) laser medium has been achieved by injection-controlled tuning. Using a pulsed dye laser as the injection source, amplified output pulses tunable between 435 and 535 nm and having a spectral width of 0.001 nm were obtained. For a 482.5 nm injection wavelength that is well matched to the XeF($C \rightarrow A$) gain maximum, output energy density and intrinsic efficiency values of approximately 8 J/l and 6 percent were achieved.**

I. INTRODUCTION

THE XeF($C \rightarrow A$) excimer transition is unique among those of the rare gas halide class because of its blue-green wavelength and exceptionally broad-band fluorescence spectrum. Free running laser oscillators operating on the XeF($C \rightarrow A$) transition typically exhibit broad laser spectra ($\sim$20 nm) centered near 485 nm [1]. The XeF($C \rightarrow A$) laser has also been wavelength tuned from about 450 to 510 nm with a spectral width on the order of a few nanometers, albeit with very low efficiency [2]–[4]. However, recent developments indicate that the electrically excited XeF($C \rightarrow A$) medium has considerable potential for development as an *efficient* optical source that is tunable throughout the entire blue–green region of the spectrum.

This conclusion is based primarily on three factors. 1) Short-pulse, high-energy electron beam (e beam) excitation of multicomponent mixtures tailored specifically to minimize transient absorption has resulted in a broad-band, free-running laser oscillator output having energy density and efficiency values comparable to those of the UV XeF($B \rightarrow X$) transition [1], [5]. 2) Using the same medium as an amplifier, a 482.5 nm output pulse having a spectral width of only 0.01 nm was obtained using dye laser injection control [6]. Moreover, the narrowed spectral output was obtained at energy density and intrinsic efficiency levels of approximately 3 J/l and $\sim$2.5 percent, respectively. 3) Our recent measurements have shown that the e-beam excited XeF($C \rightarrow A$) medium exhibits relatively high peak gain (>2 percent $\cdot$ cm^{-1}) throughout the entire 450–515 nm wavelength region, indicating that efficient tuning over a broad spectral range should be possible. In this paper, we report on our first efforts to capitialize on these characteristics by injection control of an XeF($C \rightarrow A$) amplifier. The injection source used was a dye laser tunable throughout the entire blue–green region and having a spectral width of only 0.001 nm. Injection of the dye laser pulse through a small hole in one mirror of an unstable resonator served to rapidly expand the seed beam, ensuring efficient use of the active volume [6], [7]. This technique has resulted in amplified output pulses that preserve the spectral width of the injected pulse, with energy densities exceeding 0.2 J/l throughout the entire 459–505 nm region. For an injection wavelength of 482.5 nm, a wavelength coinciding with the region of maximum gain, output pulses corresponding to an extraction energy density of approximately 8 J/l were demonstrated, indicative of an intrinsic efficiency of about 6 percent.

The details of the experimental arrangement and related diagnostics are described in Section II. In Section III, the factors affecting the net gain are summarized with particular emphasis on the importance of Kr addition to the laser mixture. Experimental results are presented in Section IV, along with a discussion of prospects for further improvement in XeF($C \rightarrow A$) laser performance.

II. EXPERIMENT

A. Electron Beam System and Reaction Cell

The experimental apparatus used in this work is illustrated in Fig. 1. A Physics International Pulserad 110 electron beam generator was used to transversely excite high-pressure gas mixtures. In order to obtain a uniform e-beam distribution and to increase the lifetime of the foil separating the low- and high-pressure regions of the cell, a stainless steel wire mesh was mounted between the e-beam cathode and the foil. The electron beam energy was 1 MeV, and the excitation pulse duration was 10 ns (FWHM), producing a pump energy density of $\sim$135 J/l, as measured by a calorimeter and Faraday cup probe.

The stainless steel reaction cell was carefully passi-

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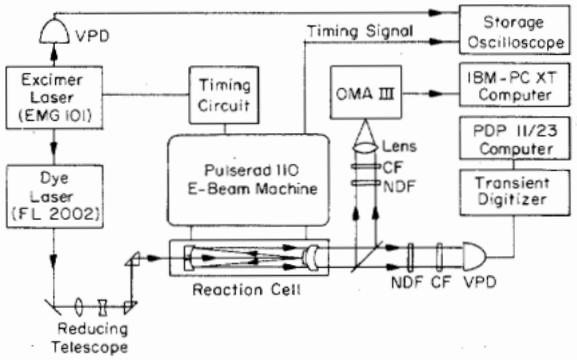

Fig. 1. Schematic illustration of the experimental apparatus, showing in particular the unstable cavity optics inside the reaction cell, the tunable injection laser source, and the timing and data acquisition systems. OMA = optical multichannel analyzer, VPD = vacuum photodiode, CF = color glass filter, NDF = neutral density filter.

vated by prolonged exposure to F_2. High-purity gas mixtures comprised of NF_3, F_2, Xe, Kr, and Ar were used [1], [5], [6]. Good gas mixing of the components was found to be essential, and was obtained using turbulent flow of the high-pressure gas components into the reaction cell. Each fresh gas mixture could be used for about ten shots before performance degradation became significant.

B. Injection Control System

An excimer-pumped dye laser system (Lambda Physik Model EMG 101E/FL2002) having a bandwidth of $\sim 5 \times 10^{-3}$ nm was used to provide injection control [6]. Use of an intracavity etalon resulted in significant additional bandwidth reduction to 9×10^{-4} nm. This seed oscillator delivered an output of up to 8 mJ in a 10 ns pulse (FWHM), tunable from 430 to 550 nm using Coumarin dyes 2, 102, and 307. A telescope was used to reduce the injection beam diameter so that most of the available dye laser pulse energy entered the unstable cavity of the *e*-beam pumped cell (Fig. 1). Due to the loss of dye laser energy caused by the beam-forming optics, the maximum injected energy was limited to ~ 1.5 mJ in these experiments.

The temporal evolution of the free-running laser, the dye laser, and the injection-controlled XeF($C \rightarrow A$) laser output were monitored by a fast vacuum photodiode detector [ITT-F4000 (S5)]. Neutral density filters were used to avoid saturation of the photodiode, and color glasses were used to define the spectral region of interest. Signals were recorded by a Tektronix R7912 transient digitizer. The time resolution of the entire system was better than 2 ns. The temporally integrated, spectrally resolved laser signal was recorded by an optical multichannel analyzer (OMA III), using a Jarrell–Ash 0.25 m spectrometer having a spectral resolution of about 0.3 nm. Additionally, the temporal relationship of the dye laser and *e*-beam pulse was monitored by a storage oscilloscope. The timing relationship between the dye laser and *e* beam was adjusted by timing circuits so that the volume-filling pass of the injected dye laser pulse overlapped the rise of the XeF($C \rightarrow A$) temporal gain profile.

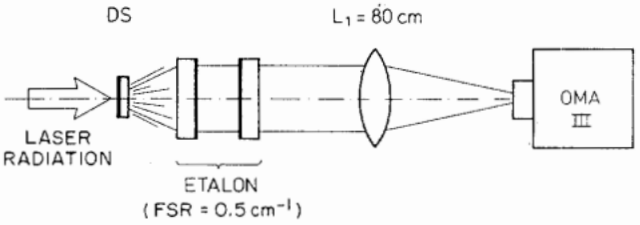

Fig. 2. Schematic illustration of the experimental arrangement used for the measurement of bandwidth. DS = diffusing screen.

C. Cavity Optics

The optical cavity used in these studies was a positive-branch confocal unstable, intracell resonator, consisting of a concave end mirror with an injection hole of 1.5 mm diameter and a coating having a high reflectivity in the blue–green region, and a convex output coupler (Fig. 1). The mirrors, having focal lengths of f_2 and $-f_1$, respectively, were separated by a distance $L = f_2 - f_1$, typically about 12 cm for our conditions, with the magnification given by the relation $M = f_2/f_1$. The ouput coupler was a meniscus lens of zero refraction power having a highly reflective coated spot on the convex side with a diameter d of 1.4 cm. With this arrangement, the output coupler could be placed in a conventional mirror holder and aligned externally. The active region was a cylindrical volume defined by the *e*-beam pumping length (10 cm) and the clear aperture having a diameter $d \times M$ cm.

Because the out coupling of the unstable cavities used was substantially greater than the value found to be optimum for a stable cavity (~ 5 percent), and since the injection hole also constitutes a large loss, significant self-oscillation (injected or not) was not possible for our conditions. Rather, in the present experiment, the role of the cavity was to serve as a beam-expanding telescope of a regenerative amplifier [6], [7]. Various cavities were examined having magnifications of 1.05, 1.08, 1.14, and 1.23, respectively. Although such small values of magnification result in a considerable sensitivity to alignment [8], they provide the long amplification path (several hundred cm) required for efficient use of the XeF($C \rightarrow A$) gain medium.

D. Bandwidth Measurement

In order to determine the spectral width of the dye laser injection pulse and of the amplified output pulse, a Fabry–Perot monitor etalon with adjustable spacing was used as illustrated in Fig. 2. Part of the amplified output was focused on a diffusing screen (DS) which served to homogeneously illuminate an air-gap etalon of adjustable spacing. By means of a long-focal-length lens ($L_1 = 80$ cm), a section of the emerging fringe pattern was imaged onto the entrance window of the OMA vidicon. Fig. 3 shows an example of a typical plot of an OMA III spectrum. Fine alignment of the setup was performed using the 488 nm line of a collinear Ar–ion laser, and after removal of the attenuators, with the throughput of the tunable dye laser radiation itself. By throughput, we mean the output

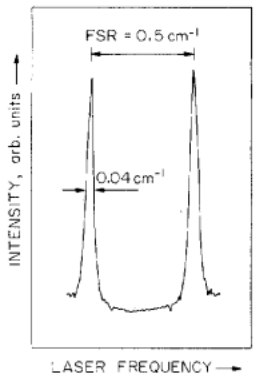

Fig. 3. Fabry–Perot etalon interferogram of a typical amplified output as observed using the OMA III vidicon.

of the injected dye laser signal after multiple reflections through the unstable resonator in the absence of *e*-beam pumping.

Using a free spectral range (FSR) of 0.5 cm^{-1}, the ultimate resolving power of the entire arrangement for linewidth measurements was 0.01 cm^{-1} or 0.00024 nm at a wavelength of 485 nm. This resolution conveniently allowed a determination of the linewidth of the injected dye laser radiation: 0.2 cm^{-1} (grating tuned) or 0.04 cm^{-1} (grating tuned + intracavity etalon of 1 cm^{-1} FSR). Using this procedure, the *e*-beam pumped multipass amplifier output was found to have essentially the same spectral width as that of the injected dye laser pulse.

III. Temporal Gain Profile

Short-pulse, high-energy *e*-beam excitation of the XeF($C \rightarrow A$) medium is characterized by a period of strong transient absorption during the excitation pulse, followed by the development of net gain in the afterglow regime [1], [5]. In early work, the combination of a relatively short gain duration (<50 ns) and a relatively low value of the peak gain (<1 percent · cm^{-1}) limited the energy and efficiency of the electrically excited XeF($C \rightarrow A$) laser to unacceptably low levels. However, in recent years, multicomponent mixtures have been developed that result in significant reduction in the transient absorption, thereby permitting much higher peak gain values (~2–3 percent · cm^{-1}), with a dramatic improvement in laser performance [1], [5], [9], [10].

A. Mixtures Containing Krypton

The addition of Kr to XeF($C \rightarrow A$) laser mixtures has been found to result in a significantly improved gain profile when *e*-beam excitation is used [5], [10]. Presented in Fig. 4 is the measured temporal evolution of the net gain for representative XeF($C \rightarrow A$) laser mixtures with and without Kr. The fractional concentrations of each constituent of the Ar–Xe–NF_3–F_2 mixture are optimized and result in broad-band extraction energy density values typically in the 1.0–1.5 J/l range when a free-running stable resonator is used [1], [5]. However, Fig. 4 vividly illustrates the significant reduction in the initial absorption and the increase in peak gain when Kr is added to the

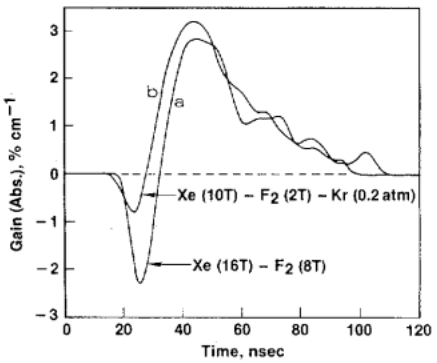

Fig. 4. Temporal evolution of the XeF($C \rightarrow A$) net gain profile measured at 488 nm using an Ar-ion probe laser for mixtures comprised of 6.5 atm Ar, 16 torr Xe, 8 torr NF_3, and 8 torr F_2 (a), and 6.5 atm Ar, 10 torr Xe, 8 torr NF_3, 2 torr F_2, and 150 torr Kr (b).

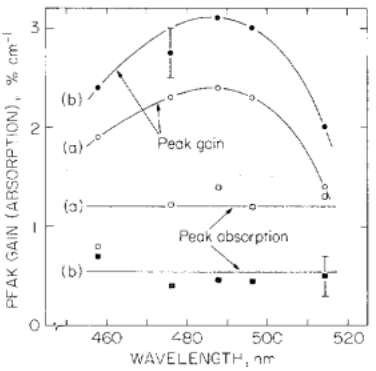

Fig. 5. Wavelength dependence of the *peak* values of gain and initial absorption for mixtures comprised of 6.5 atm Ar, 16 torr Xe, 8 torr NF_3, and 8 torr F_2 (a), and 6.5 atm Ar, 10 torr Xe, 8 torr NF_3, 2 torr F_2, and 300 torr Kr (b).

mixture and all constituent fractional concentrations are reoptimized. The improved gain profile typical of Kr-containing mixtures has been found to increase the broad-band output energy and intrinsic efficiency of a stable, free-running oscillator to levels comparable to those of the UV XeF($B \rightarrow X$) transition [5]. The wavelength dependence of the peak values of gain and initial absorption for mixtures with and without Kr are presented in Fig. 5. These results are typical of Kr partial pressures in the 150–600 torr range, and show that the peak gain is increased significantly and the initial absorption is decreased throughout the entire wavelength range of interest.

In our initial work on injection control [6], an optimized Ar–Xe–NF_3–F_2 mixture typical of the conditions of Figs. 4 and 5 was used. However, for the experiments reported herein, an optimized Kr-containing mixture was utilized. Of course, the higher value of peak gain typical of Kr mixtures results in greater amplification of the injected dye laser pulse. As important, however, is the fact that with Kr present in the mixture, the initial absorption of the injected pulse is greatly reduced (Fig. 4), thereby increasing the energy available for amplification. For this reason, the presence of Kr in the mixture has an even greater beneficial effect when the XeF($C \rightarrow A$) medium is used as an amplifier than when used as a free-running oscillator [5]. Additionally, for the conditions of Figs. 4 and

5, the concentration of Kr_2F is very large [10]. Since the Kr_2F excimer is an absorber of UV radiation, its presence significantly reduces the possibility of competitive oscillation on the XeF($B \rightarrow X$) transition [10].

IV. Experimental Results and Discussion

A. Timing Considerations

The approximate temporal relationship among the injected dye laser pulse, the *e*-beam excitation pulse, the amplified output pulse, and the free-running broad-band XeF($C \rightarrow A$) laser oscillator output are shown in Fig. 6. Figs. 4 and 6 show that the duration of the dye laser pulse and the gain risetime are both on the order of 10–20 ns, a time nearly the same as that required for the injected pulse to fill the cavity. For this reason, control of the timing of the dye laser pulse with respect to the firing of the *e* beam was found to be a difficult and critical aspect of the present experiment. The problem was further complicated by the fact that a short period of initial absorption accompanies the *e*-beam firing (Fig. 4), although at a much reduced level when using mixtures containing Kr as described previously.

Presented in Fig. 7 is the dependence of the amplified 482.5 nm pulse energy on the delay time between the injection of a 1 mJ dye laser pulse and the firing of the *e* beam. This figure shows that for a magnification M of 1.08, for which approxmately 86 percent of the dye laser energy is reflected back out through the injection hole, the temporal window corresponding to optimum timing is only 10–15 ns. For an M value of 1.05, the window was slightly larger, reflecting the fact that the transit time of the dye laser pulse through the cavity increases as M decreases, thereby relaxing the timing constraint somewhat. For the same reason, the optimum temporal window was reduced to about 5 ns for an M value of 1.23.

B. Magnification Effects

In addition to a significant dependence on timing, the amplified output pulse energy also exhibited a strong dependence on cavity magnification for the specific conditions of our experiment. Fig. 8 shows the dependence of the 482.5 nm output energy on M for near optimum timing (Fig. 7) and a 1 mJ injection pulse energy. As M is reduced from 1.23, the output energy increases, a reflection of the increase in cavity feedback for the lower M values. However, as M approaches unity, nearly all the injected dye laser energy is reflected back out through the 1.5 mm diameter injection hole. Indeed, Fig. 8 shows that the output energy decreases rapidly as the magnification is reduced to 1.05. Additionally, optical alignment was found to be very difficult using the $M = 1.05$ cavity [8].

C. Output Energy and Efficiency

For the conditions of Figs. 7 and 8, the *e*-beam energy deposition was measured and found to be approximately 135 J/l, a value consistent with calculated and measured values of medium properties [1]. Since the active volume defined by the mirror spacing and magnification values varied from 16.8 to 20.4 cm^3 for our conditions, the maximum 149 mJ output obtained at 482.5 nm corresponds to an energy density of ~8 J/l and an intrinsic efficiency of approximately 6 percent. On a volumetric basis, these values are actually higher than those typical of room temperature XeF($B \rightarrow X$) laser operation, and are comparable to XeF($B \rightarrow X$) performance at the 450 K temperature found to be optimum for that laser [11], [12]. This is rather surprising in view of the fact that the $C \rightarrow A$ quantum efficiency is ~25 percent less than that of the $B \rightarrow X$ transition. However, because of the strongly repulsive nature of the XeF(A) state, the $C \rightarrow A$ laser does not suffer from lower level population buildup as is the case with

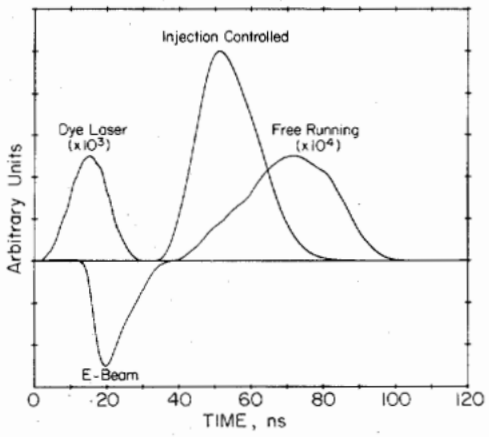

Fig. 6. Temporal relationships of the dye laser, the *e*-beam excitation pulse, the amplified XeF($C \rightarrow A$) output, and the broad-band and XeF($C \rightarrow A$) output with the system operating as a free-running oscillator.

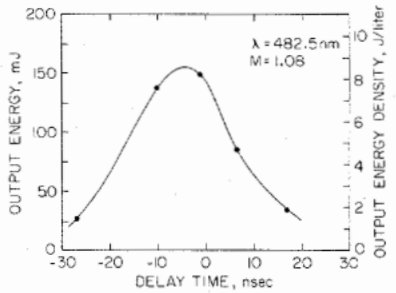

Fig. 7. Dependence of the amplified XeF($C \rightarrow A$) output energy on the delay time between a 482.5 nm dye laser pulse and firing of the *e* beam. The energy of the dye laser pulse entering the cavity was 1 mJ, approximately 86 percent of which was reflected back out through the injection hole. The mixture was comprised of 6.5 atm Ar, 8 torr Xe, 8 torr NF_3, 1 torr F_2, and 300 torr Kr.

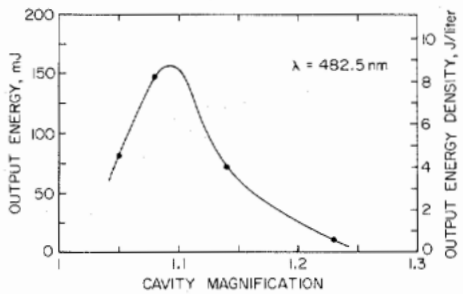

Fig. 8. Dependence of the 482.5 nm amplified output pulse on cavity magnification for optimum timing and conditions otherwise similar to those of Fig. 7.

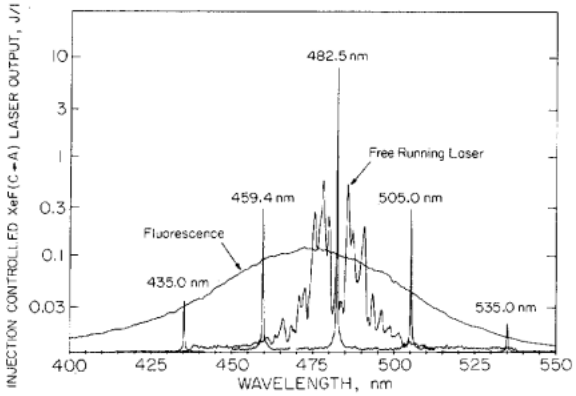

Fig. 9. Qualitative comparison of superimposed time integrated spectra of the XeF($C \rightarrow A$) fluorescence, the injection-controlled output of five separate shots at several wavelengths, and a typical free-running oscillator spectrum, all for representative conditions.

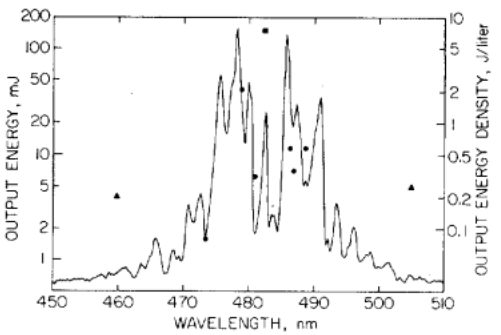

Fig. 10. Measured amplified XeF($C \rightarrow A$) output energy for selected wavelengths for an *injected* dye laser pulse of approximately 1 mJ, along with a typical free-running spectrum, the intensity of the latter in arbitrary units for comparison. The cavity M values were 1.05 (▲), 1.08 (■), and 1.14 (●) (see Fig. 8).

the $B \rightarrow X$ laser. Additionally, the 6.5 atm Ar–Kr buffer mixture used in the present work results in B–C state mixing and vibrational relaxation times of approximately 0.1 ns [10], [13], which are very much less than those typical of optimum $B \rightarrow X$ laser mixtures using Ne as the buffer at pressure of ~3 atm [11], [12]. Since both lower level buildup and slow vibrational relaxation adversely affect XeF($B \rightarrow X$) laser energy and efficiency [11], [14], apparently the XeF($C \rightarrow A$) medium has advantages in this regard, provided the level of broad-band transient absorption is controlled kinetically and the characteristically slow build up of optical flux that usually limits oscillator performance is overcome by using the $C \rightarrow A$ medium as an amplifier.

D. Wavelength Tuning

In order to determine the range within which the XeF($C \rightarrow A$) medium can be efficiently tuned, the wavelength of the injected pulse was varied from 435 to 535 nm. Fig. 9 provides an illustrative comparison of the spectra of several injection-controlled shots and a free-running oscillator spectrum, along with the XeF($C \rightarrow A$) fluorescence spectrum. Because of the large cavity loss described previously, the maximum free-running output energy was always less than 0.1 mJ for our conditions. However, several mJ of amplified output were obtained for injection wavelengths as low as 459.4 nm and as high as 505 nm. In fact, amplification of the injected signal was observed for wavelengths as low as 435 nm and as high as 535 nm.

Presented in Fig. 10 is the measured output energy as a function of wavelength for several different cavities, along with a typical free-running spectrum for comparison. The specific injection wavelengths were chosen to correspond to the peaks and absorption valleys that are always apparent in the free-running XeF($C \rightarrow A$) laser spectrum. This figure shows that the wavelength dependence of the minima observed in the amplified output correlates reasonably well with the locations of the absorption valleys in the free-running spectrum. The discrete absorption is due primarily to phototransitions from Xe($^3P_2$, $^3P_1$) atoms to higher Rydberg levels [1], [15].

While all the points shown in Fig. 10 correspond to near optimum timing between the dye pulse injection and e-beam firing (Fig. 7), only the 482.5 nm point was obtained using optimum cavity magnification (Fig. 8). Additionally, the measured dye laser throughput for a bare cavity was occasionally less than expected on the basis of the cavity magnification value, a condition found to be caused by significant mirror surface deterioration under certain conditions. For these reasons, we feel that, with the exception of the 482.5 nm value, the measured amplified output energies of Fig. 10 represent lower limits. Correcting the values of Fig. 10 for differences in cavity magnification (Fig. 8) and for the estimated effect of mirror surface deterioration suggests that, except for wavelengths coinciding with discrete absorption transitions, output energy density values >1 J/l should be attainable throughout the entire blue–green region of the spectrum.

V. Summary

The results of this investigation provide encouraging evidence that the electrically excited XeF($C \rightarrow A$) medium has significant potential for development as an efficient optical source of high brightness that is tunable throughout a large portion of the blue–green spectral region. Moreover, the usually high values of extraction energy density and of intrinsic efficiency that were obtained for an injection wavelength matched to the maximum gain suggest that the XeF($C \rightarrow A$) medium may have the potential to rival its UV rare gas–halide counterparts for certain selected applications requiring high energy and efficiency.

Although relatively efficient (>0.1 percent) tuning has been demonstrated for wavelengths as low as 459.4 nm and as high as 505 nm, XeF($C \rightarrow A$) amplifier performance has been limited in the present investigation by the combination of a short active length (~10 cm), undesirably low values of cavity magnification (<1.3) required to compensate for the former, and a critical sensitivity to timing. However, it is clear that these factors do not represent fundamental limitations. Considering that the gain of the e-beam excited XeF($C \rightarrow A$) medium is relatively high (>2 percent · cm^{-1}) over a 100 nm bandwidth centered at 480 nm, significant improvement in performance

should be forthcoming as a result of pumping geometries which are better suited to optimization of the laser cavity.

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Gerd Marowsky, photograph and biography not available at the time of publication.

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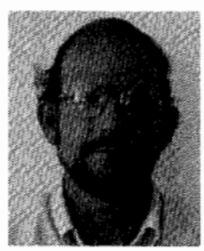

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